Dynamical Dark Energy and Tensions: A Story of Conflicting Datasets

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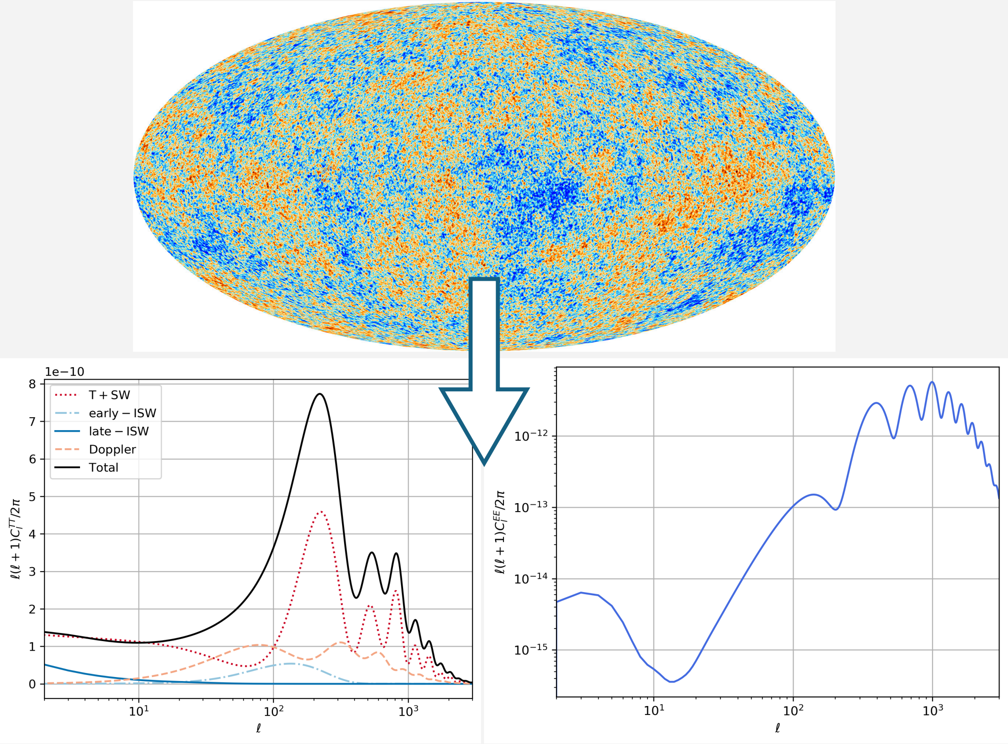
Key Datasets

CMB

- We can measure the anisotropies of the temperature and polarisation of the CMB photons
- Different sections of the power spectrum generated from this data are sensitive to various cosmological parameters
- Peaks represent extremums of the acoustic waves of the photon-baryon fluid at decoupling



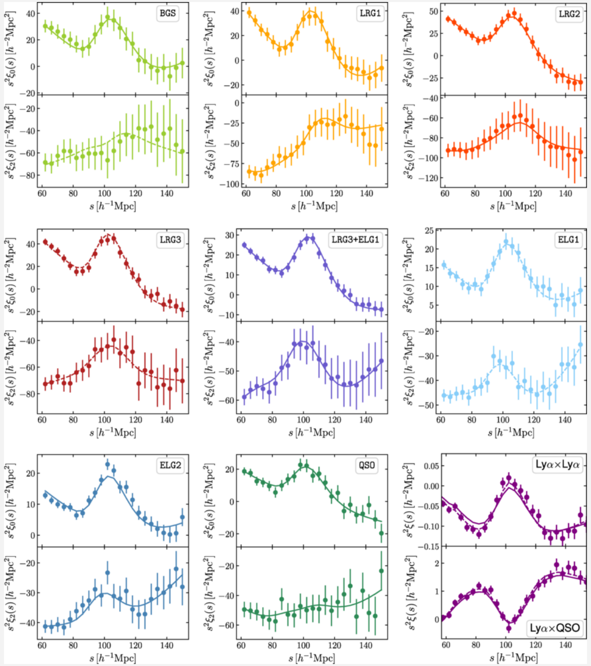
Planck CMB map (credit ESA) and TT EE power spectra generated using CLASS (http://class-code.net/)

BAO

- The acoustic oscillations of the photon-baryon fluid are frozen at decoupling as photons become free-streaming
- Leads to additional power in the tracers of the matter density at scales corresponding to the sound horizon at decoupling
- Surveys such as DESI and SDSS build maps of the matter distribution
- We can use this sound horizon scale as a standard ruler to constrain the cosmological parameters

$$d_M(z) = \frac{1}{1+z}\frac{1}{|\Omega_k|^{\frac{1}{2}} H_0} \sin_k\left(|\Omega_k|^{\frac{1}{2}} \int_0^z \frac{d\tilde{z}}{E(\tilde{z})} \right)$$

- With BAO alone, we can only measure the ratio between the distances and the sound horizon at decoupling.



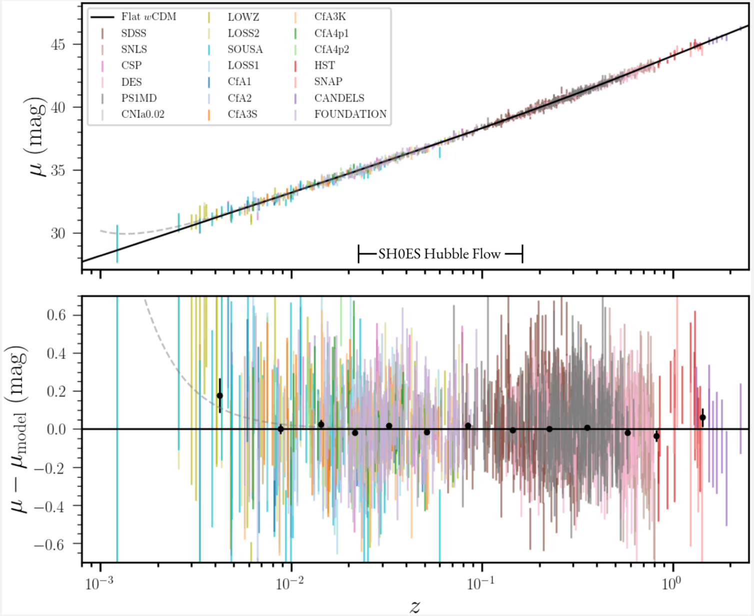
Plot from DESI DR2 (https://doi.org/10.1103/tr6y-kpc6) showing the BAO signal on monopole and quadrupole moments of matter density tracers (first 8 figures).

SNe

- Type Ia supernovae have a known correlation between the peak and decay rate of their lightcurves
- This allows the SNe datasets to be normalised with respect to the absolute magnitude of a standard SNe luminosity

$$d_L(z) = (1+z)\frac{1}{|\Omega_k|^{\frac{1}{2}} H_0} \sin_k\left(|\Omega_k|^{\frac{1}{2}} \int_0^z \frac{d\tilde{z}}{E(\tilde{z})} \right)$$

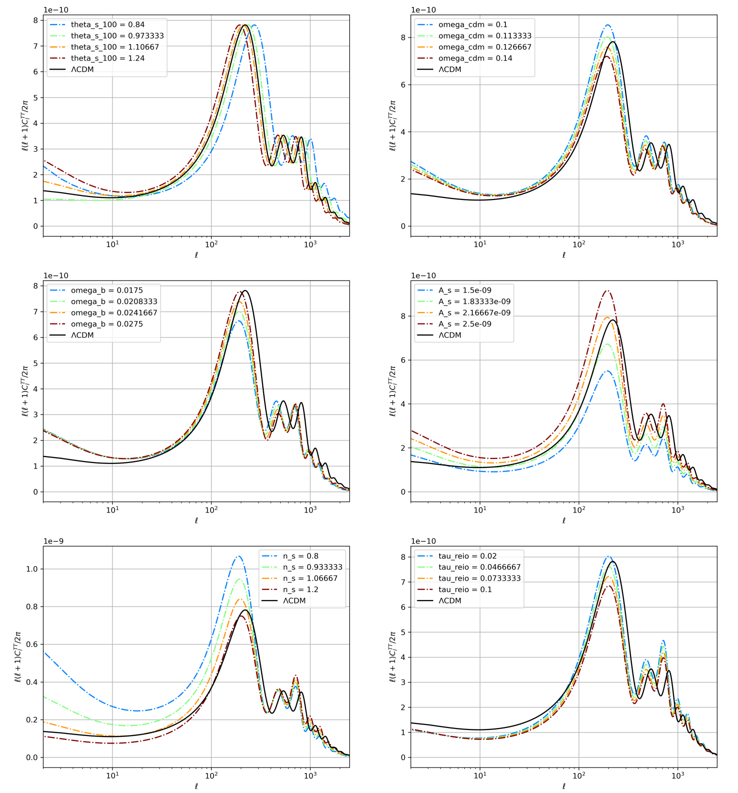
- Similar to BAO, SNe require a geometric anchor to break the degeneracy and obtain the absolute distance scales



Plot of the Pantheon+ (https://doi.org/10.3847/1538-4357/ac8e04) SNe distance modulus μ with the redshift. The solid line represents the best fit ΛCDM for these data

Flat ΛCDM Cosmology

- The standard model of cosmology is the flat ΛCDM cosmology which is described by 6 parameters (usually using the set $\{\theta_s, \Omega_c h^2, \Omega_b h^2, A_s, n_s, \tau_{\text{reio}}\}$)
- Works remarkably well at describing all three types of measurements
- However, when combining different measurements issues arise
- Each sets of data prefer a different ΛCDM cosmology



Plot of the CMB TT power spectrum generated using CLASS showing how each ΛCDM parameter affects the spectrum

Why should we look beyond ΛCDM Cosmology?

Dynamical Dark Energy

- The distances measured by the BAO and SNe are related by the distance duality relation
- We can look at the relative distance scales of these measurements with redshift and compare with the best fitting ΛCDM predictions
- We can see that when we combine the datasets, a dynamical dark energy fits all the datasets

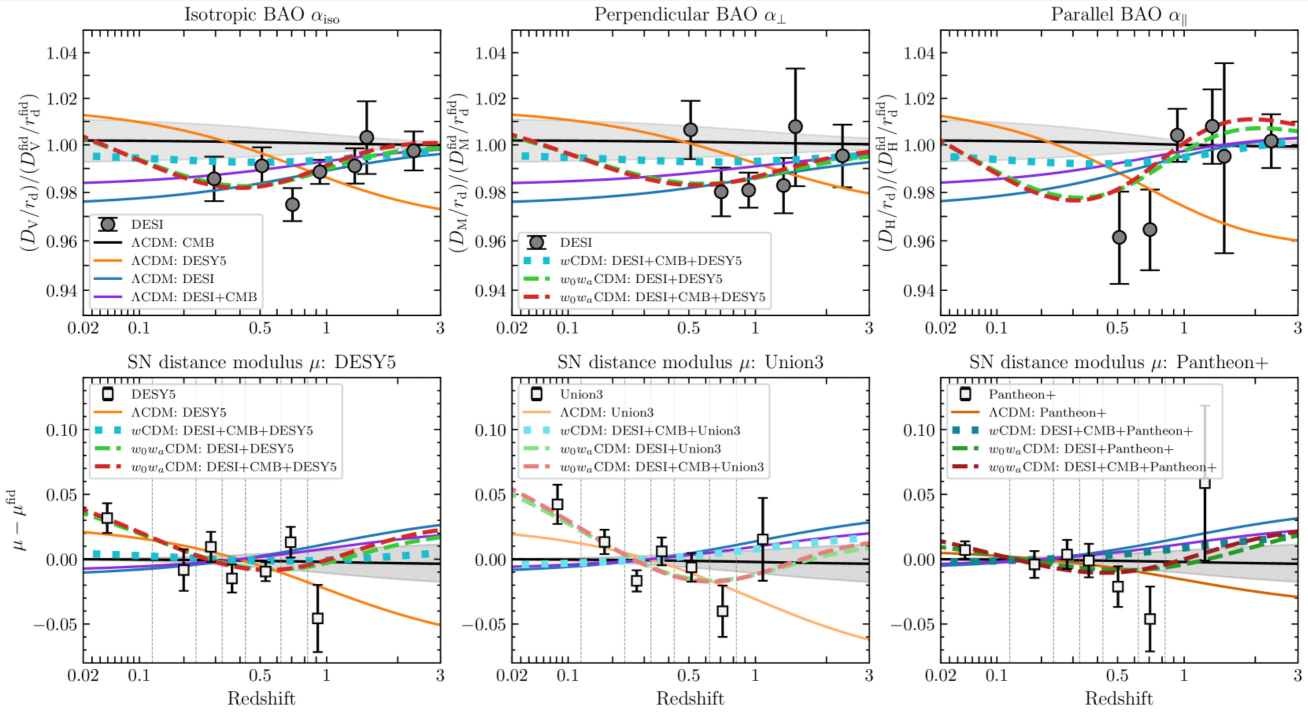
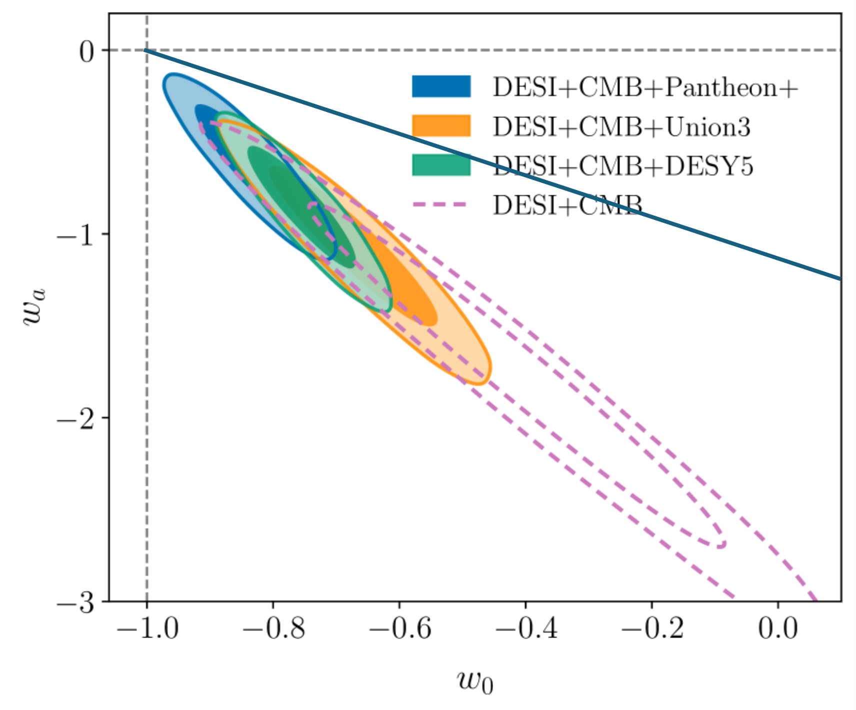


Fig. 1. Plot from DESI DR2(https://doi.org/10.1103/tr6y-kpc6) showing how the residuals of the binned distance measurements for BAO and SNe fit with respect to ΛCDM and CPL best fits.

Scalar Fields?

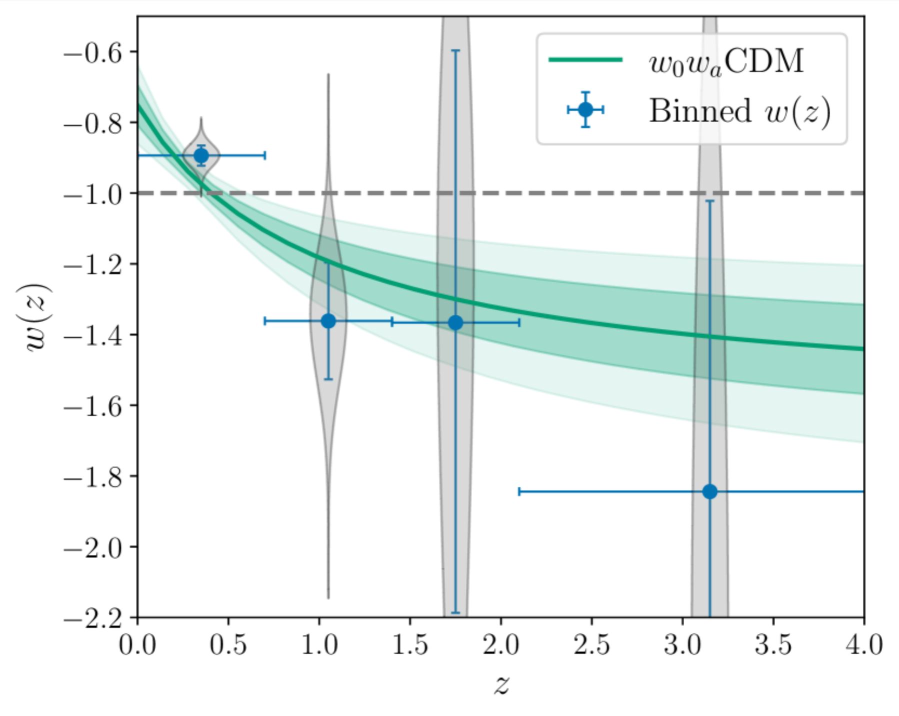
- A possible theoretical model for dynamical dark energy is a scalar field
$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + \mathcal{L}_{SM}\right]$$
- The canonical scalar field must have an equation of state
$$w = \frac{p_\phi}{\rho_\phi} = \frac{\frac{1}{2}\dot{\phi}^2 + V}{\frac{1}{2}\dot{\phi}^2 - V} \in [-1, +1]$$
- The CPL parametrisation is a first order Taylor expansion of this equation of state in a: $w = w_0 + w_a(1-a)$
- Different regions of the parameter space correspond to different types of scalar field evolutions



Plot from DESI DR2 (https://doi.org/10.1103/tr6y-kpc6) on the constraints on the parameter space of CPL. The line above indicates the lower limit of a thawing quintessence model $w_0 + w_a = -1$

Characteristics of Dynamical Dark Energy

- Observations have a preference for a dynamical dark energy with breaks the null energy condition in the past $w < -1$ but at present time, it has crossed the phantom divide and $w_0 > -1$
- This means that dark energy violates the null energy condition according to the best fit model
- Possible resolutions from a theoretical aspect would have to be more complicated with an interacting scalar field or non-canonical kinetic terms (k-essence scalar fields)
- However these usually result in more problems elsewhere

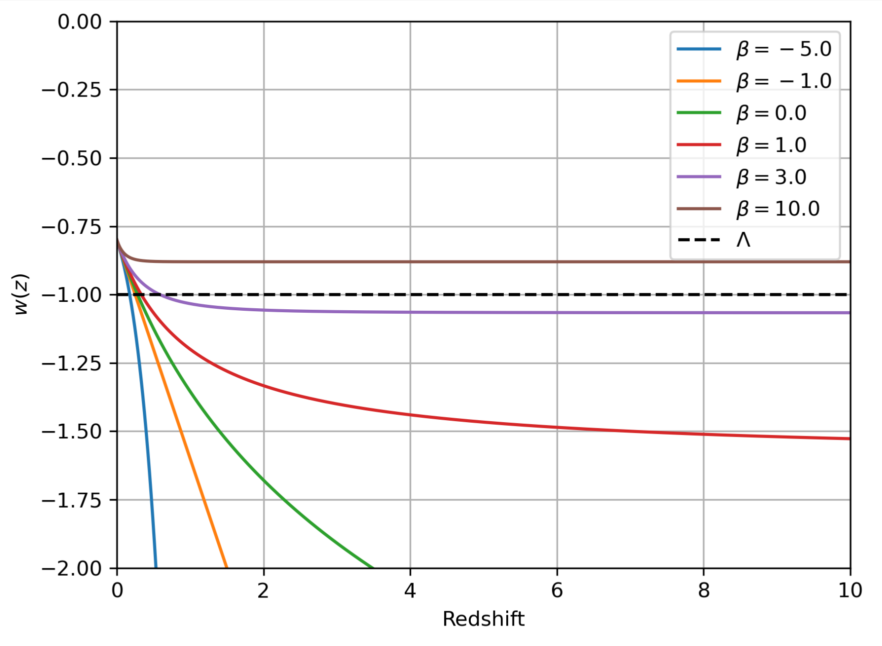


Model independent reconstruction of the equation of state from DESI DR2 (https://doi.org/10.1103/tr6y-kpc6)

Parametrisation of the Equation of State

- By far the most popular parametrisation of the equation of state is the CPL parametrisation $w = w_0 + w_a \frac{1}{1+z}$
- However there are multiple other attempts at parametrisation of the dark energy equation of state $w = w_0 + w_{\text{lin}}(1+z)$ and $w = w_0 - w_{\log} \ln(1+z)$
- We wanted to compare these parametrisations to see if the data recovers CPL even when we give it an additional degree of freedom to vary between models

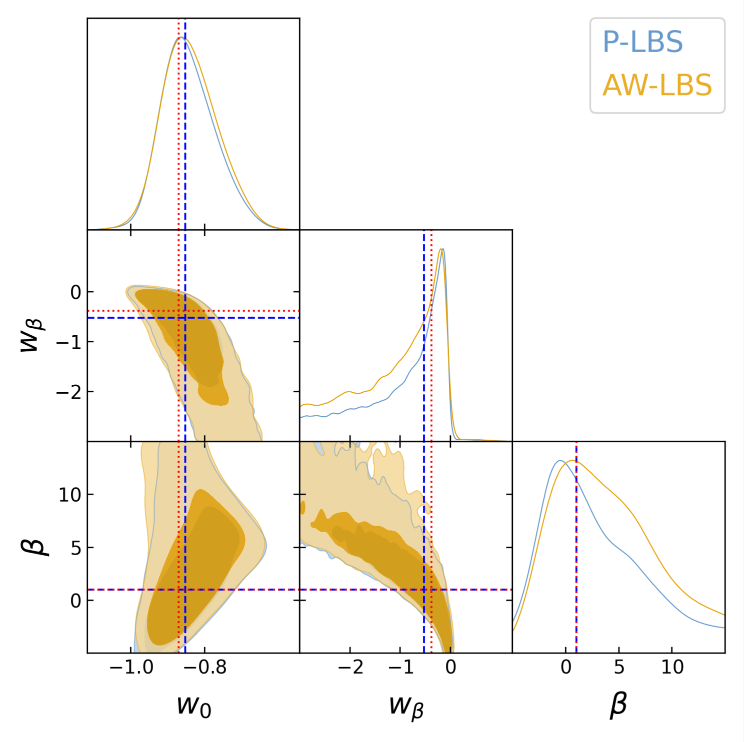
$$w = w_0 - w_a \left[\frac{(1+z)^{-\beta} - 1}{\beta} \right]$$



Plot of the variation of the equation of state with variation in β from work in (https://arxiv.org/pdf/2507.11432)

Preference for CPL?

- We conducted analysis of this model with the following datasets:
  - CMB: Planck 2018 (TT,TE,EE high and low ℓ) or ACT DR6 (TT, TE, EE high ℓ) with WMAP (truncated) and low ℓ EE Planck Sroll2
  - CMB lensing: ACT DR6 with Planck PR4 NPIPE
  - BAO: DESI DR2
  - SNe: Pantheon+
- We found the constraints to be fairly consistent with CPL with similar model preferences
- While the value of w_a is poorly constrained, we see that it definitely still prefers a phantom crossed DE



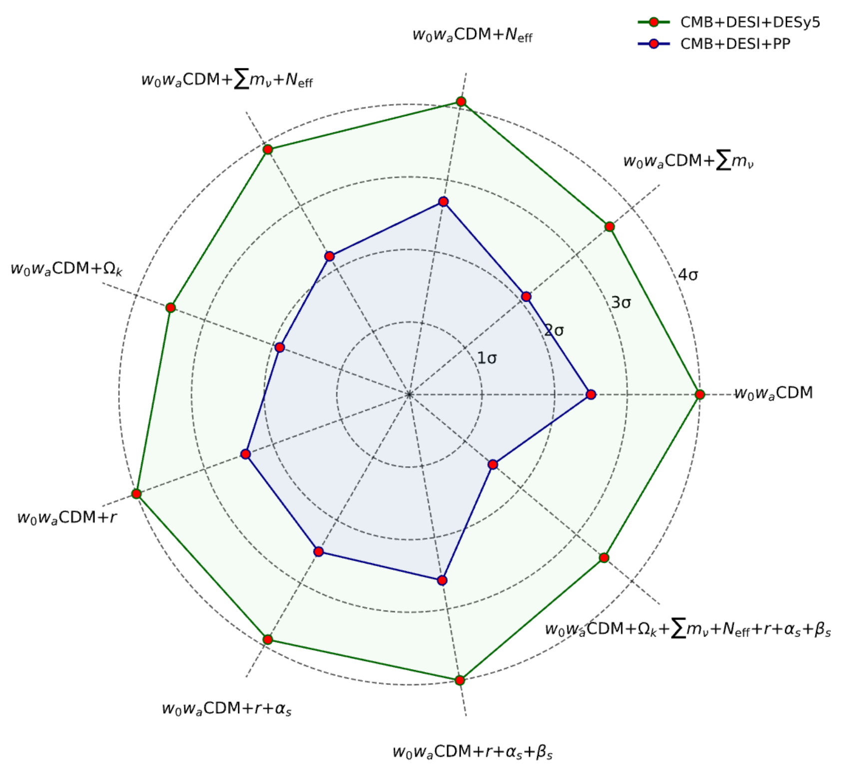
Constraints on the dark energy parameters from (https://arxiv.org/pdf/2507.11432)

Physics beyond the Standard Model of Cosmology

- There are of course other extensions of $\Lambda\mathrm{CDM}$ which touch on various other aspects of the physics of the universe
- A non-exhaustive list of extensions are:
  - Curvature: Ω_k the contribution of the spatial curvature to the Friedman equation
  - Neutrinos: $\sum m_\nu$ the sum of the neutrino masses can be constrained in cosmology but the $\Lambda\mathrm{CDM}$ values are in tension with neutrino oscillation experiments
  - Relativistic species: N_{eff} number of effective neutrino species
  - Inflation parameters: $r = \frac{A_t}{A_s}$ the tensor to scalar ratio, $\alpha_s = \frac{\mathrm{d}n_s}{\mathrm{d}\ln k}$ the running of the spectral index and $\beta_s = \frac{\mathrm{d}^2 n_s}{\mathrm{d}(\ln k)^2}$ the running of the running of the spectral index

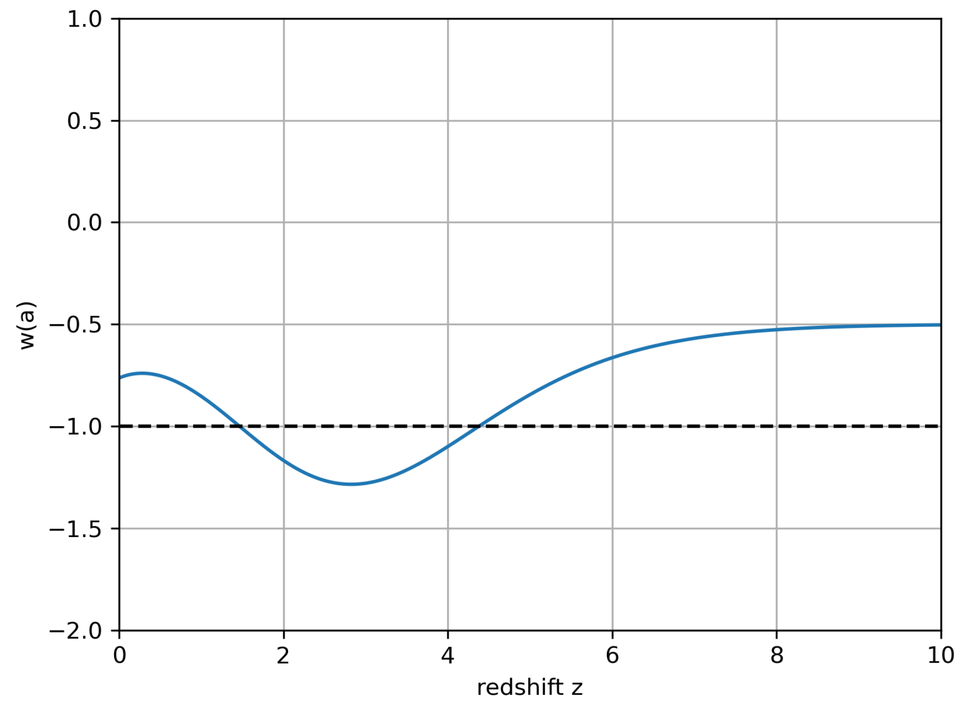
Preference for a Phantom-Crossed Dynamical Dark Energy

- We compared the extension models in the case of both a constant dark energy and dynamic dark energy
- We see a consistent preference for dynamic dark energy over a cosmological constant in all other physical extensions
- Shows the robustness of the preference



Plot of the preference of dynamical dark energy in all model combinations with other physical phenomena (work in prep)

Out of Left Field?



Work in Progress